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System Wide Life Cycle Benefits of Fly Ash

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ABSTRACT

The use of recycled materials in highway construction has the potential to achieve significant benefits affecting the triple-bottom line (environment, prosperity and society). Such benefits include reducing the need for mining virgin materials and transportation (in-situ applications), reducing environmental impacts of processing and transportation, and reducing life cycle costs. Although state departments of transportation (DOTs) have been in the forefront of introducing recycled materials, they have not been able to clearly convey the benefits in a quantitative and transparent manner using easily understood metrics. The main reason for this is the difficulty in tracking the quantities of recycled materials used in state DOT projects. To better define the benefits of using recycled materials, the Recycled Materials Resource Center (RMRC) is undertaking a project with two objectives. The first objective is to develop a means of tracking and reporting the recycled material quantities used in state DOT projects annually. The second objective is to provide a tool to quantitatively analyze and report the environmental and life cycle assessment of using recycled materials in highway construction. A suitable method was recommended after studying how RMRC member states currently track their recycled materials quantities. Subsequently, a Life Cycle Assessment analysis of three environmental parameters, energy use, water consumption and CO_2 emissions, showed significant environmental benefits when states used recycled industrial byproducts such as fly ash.

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1 INTRODUCTION AND BACKGROUND

Roadways around the US are continuously being constructed and rehabilitated, hence requiring large amounts of natural raw materials, producing wastes, and consuming energy.[1,3] In order to reduce these economic and environmental costs, state Departments of Transportations (DOTs) have been reusing highway construction materials in various DOT projects.

The Recycled Materials Resource Center (RMRC) and many governmental agencies have developed fact sheets on various recycled materials and industrial byproducts for their use in highway construction applications. These fact sheets typically have addressed the engineering properties and environmental suitability issues relevant to various applications and in some cases incorporated design guidelines and construction specifications. However, what is lacking is direct information on sustainability assessment characteristics, i.e., greenhouse emissions, energy and water consumption, and life cycle cost benefits. Agencies may track system-wide use of quantities for major recycled materials such as fly ash in concrete, recycled asphalt pavement, recycled concrete aggregate, etc. but they can not readily calculate the benefits accrued by substitution of these materials for conventional materials. Although state DOTs have been in the forefront of introducing recycled materials, they have not been able to clearly convey the benefits in a quantitative and transparent manner using easily understood metrics.

1.1 *Objectives*

The first objective of this study is to develop a means of reporting and tracking the recycled materials used by member DOTs. Member states have had varying levels of success in tracking these quantities; hence it was proposed to collect information on the most successful data tracking system.

The second objective of this study is to develop a tool by which the state system-wide material use quantities can be used to calculate the life cycle benefits associated with the incorporation of these recycled materials and industrial byproducts to highway pavement construction. In order to realistically quantify the output of such a tool, data on the recycled materials quantities used by each member state DOT was collected and analyzed. For the purposes of this paper, the analyses focus on the use of fly ash in highway pavement construction.

1.2 *Member States*

The following are the RMRC member state DOTs that have provided data for this study:

- Colorado
- Georgia
- Illinois
- Minnesota
- Pennsylvania
- Virginia (pending)
- Wisconsin

2 DATA COLLECTION

2.1 *LCA Tool Methodology*

One goal of this project was to provide DOTs with a quantitative tool to convey the benefits of using recycled materials that is both easy to use and to understand. The first step in achieving this goal was to examine existing publically available pavement life cycle assessment (LCA) tools. The use of an LCA can assist in a better understanding of the environmental impacts of products through-out their life cycle, cradle-to-grave, and provide decision makers with relevant data in order to make a better informed decision.[5,6] The International Organization for Standardization (ISO) 14040 series provides general principles and framework for an LCA study, detailing four phases of an LCA: definition of goals and scope, inventory analysis, impact assessment and interpretation. In general LCAs should have defined system boundaries, functioning units and inputs/outputs.[5,6] For most pavement LCAs the defined system boundaries are: materials, construction, use, maintenance, and end-of-life.[9] For the purpose of this project, we examined four existing publically available LCA tools focusing on the scope of each tool, including the system boundaries and environmental impacts. The four tools were selected based on their availability to the public and the locations they were developed. Table 2.1.1 shows each tool and some basic information about the structure of each tool.

Table 2.1.1: LCA tools researched for this project, based on Table 1.2 from Santero, et al., 2011[2, 4, 7, 9, 10]

Tool	*Developer*	*Interface*	*Pavement Types*
asPECT	Transport Research Library	GUI	asphalt
GreenDOT	AASHTO	spreadsheet	all
PE-2	Michigan Technical University	web-based	all
PaLATE	UC-Berkeley, RMRC	spreadsheet	all

2.2 *Data Collection tool Methodology*

In the first phase (2013) of data collection, a survey was conducted with seven-member state DOTs (CO, GA, IL, MN, PA, VA and WI) in order to determine the degree to which recycled materials were used and tracked by member states. Additionally, the survey served to determine the need and usefulness of a materials tracking system. The results of this survey helped in updating the current RMRC factsheets, and in gauging the extent of recycled materials use in member DOTs.

The survey results showed that while many DOTs do use commonly recycled materials (such as recycled asphalt pavement, recycled concrete aggregate and fly ash) most DOTs tracked neither the breakdown of recycled materials used per each pavement layer nor the total annual quantities used. Overall, member states agreed that the availability of a recycled materials tracking tool would be useful.

Four out of six of the member states surveyed (CO, IL, MN, WI) already have a database for tracking as-let quantities for standard bid items. Additionally, two of these four states (IL, WI) along with the other two (GA, PA), who did not already have a tracking system in place, felt that developing a similar tracking system adapted to each state's database would be useful.

Among the comments from the participating member state DOTs, many indicated that it would be difficult and time consuming to track recycled material quantities and were unsure of the benefits of doing so. These thoughts were reflected during the data collection phase of this project. For example, while all states surveyed reported using recycled asphalt shingles (RAS), only three were able to report the annual quantities used. This uncertainty regarding the benefits of tracking recycled materials is one of main reasons this life cycle assessment project was conducted.

In the second phase of data collection, RMRC member state DOTs (except CO) were asked to report quantities of recycled materials for the calendar or fiscal year of 2013. These quantities could not be tracked effectively by any of the DOTs and hence were not readily available. However, information on as-let items for all projects within this time period was available from five (IA, WI, MN, PA and GA) of the DOTs (VA data is forthcoming). In order to calculate the quantities of recycled materials from as-let material quantities, a set of assumptions regarding average design specifications needed to be determined for each state DOT (i.e. the percent replacement of cement with fly ash, and pavement dimensional specifications). This was established through interviews and correspondence with engineers from these member states. These assumptions and averages were then used to calculate the amounts of recycled materials used in hot mix asphalt (HMA), concrete mixes and base course layers.

Using these material quantities, an LCA was conducted. The environmental benefits of using fly ash were quantified in comparison to using conventional virgin materials.

3 LIFE CYCLE ASSESSMENT

3.1 *Overview of existing LCA Tools*

Each LCA tool assessed for this study follows the four phases of an LCA defined by the ISO; definition of goals and scope, inventory analysis, impact assessment and interpretation. The goal of using LCA for this study is to calculate the environmental impacts of using recycled materials or industrial by-products in highway pavement, specifically focusing on Green House Gas (GHG) emissions. Table 3.1.1 provides a comparison of the four tools researched for this project based on the common system boundaries of pavements. Of the four LCA tools, PaLATE furthers its impact assessment by also including energy and water consumption, RCRA hazardous waste, particulate matter and human toxicity potentials emissions as well as an option to act as a Life Cycle Cost Analysis tool.[4] GreenDOT, developed by AASHTO for state DOTs, is unique in that it can be used as a project specific tool or for annual statewide totals. GreenDOT is also unique in that it calculates emissions of the electrical components of a highway, i.e. traffic signals.[2] The only tool of the four researched that takes into account the effects of traffic delay is PE-2 developed by Michigan Tech.[7]

Table 3.1.1: LCA overview by phase boundaries, based on Table 1.3 from Santero, et al., 2011[2, 4, 7, 9, 10]

	Materials		Construction		Use				Maintenance				End-Of-Life				
Tool	Extraction and Production	Transportation	Onsite Equipment	Traffic Delay	Carbonation	Lighting	Albedo	PVI	Extraction and Production	Transportation	Onsite Equipment	Traffic Delay	Onsite Equipment	Transportation	Landfilling	Recycling Processes	Carbonation
asPECT	•	•	•						•	•	•		•	•	•	•	
GreenDOT	•	•	•						•	•	•		•	•			
PaLATE	•	•	•						•	•	•		•	•	•	•	
PE-2	•	•	•	•					•	•	•	•	•	•	•		

The LCA tool asPECT, the Asphalt Pavement Embodied Carbon Tool developed by TRL, follows the material used in asphaltic pavement from raw material acquisition through the end of life processes of disposing of or recycling the pavement materials.[10] The main goal of asPECT is to calculate GHG emissions based on ten life cycle stages for a road. GHG emissions in CO_2 equivalents are calculated based on user inputs of materials, fuels, modes of transport, construction operations and asphalt plant location, energy use and available mixtures.[10] asPECT allows the materials production, construction and maintenance to be user defined. While this would be advantageous for an individual project, the tool was too specific for the purposes of a system-wide study. asPECT was also difficult to update if necessary. One other major disadvantage in using asPECT for this project was that asPECT is only capable of analyzing asphaltic pavements, which would not have allowed us to conduct a complete analysis. The only state in our study using fly ash in HMA was Georgia.

Another LCA tool studied was PE-2 developed by Michigan Technical University.[7] PE-2 estimates the life cycle emissions associated with construction, maintenance and use of roadway. It use unique from the other LCA tools addressed in this paper in that it is the only tool that has a web-based interface and it is the only tool that takes into account the costs of traffic delay caused by construction operations.[7] The tool was designed solely for projects based in Michigan and is limited by four pre-defined construction operations, i.e. hot mix asphalt cold milling and overlay, and the few materials in its database. While PE-2 was found to be a good tool to use for a quick estimate of environmental costs, it was not considered to be capable of a more in-depth analyses needed for this project.

GreenDOT, developed by AASHTO specifically for state DOTs, calculates CO_2 emissions from operations, construction and maintenance projects. GreenDOT includes emissions based on four categories: electricity, materials, on-road vehicles, and off-road vehicles. These categories encompass all material production and transportation and construction operations environmental costs, as well as the environmental costs of streetlights, lamps and other lighting used in roadways. Not only is GreenDOT able to calculate emissions for specific projects, but it is also able to be used for system wide emissions.[2] Overall GreenDOT was found to be user friendly, but limited in the amount of materials and equipment in its databases. The user must have knowledge of the Excel coding language VBA.

Lastly, PaLATE LCA tool (developed by UC-Berkley and RMRC) follows the production of materials and construction, maintenance, and end-of-life processes. Initial materials input are analyzed based on the equipment used to produce and transport them to the construction site. Emissions due to construction, maintenance, and production are calculated based primarily on the equipment used in all processes. These processes include paving, milling, in-place recycling and concrete demolition to name a few.[4] Many of the outputs of PaLATE are heavily based upon the volumes of materials used and the parameters of the equipment used, such as the productivity and fuel consumption of each machine used. This allows for PaLATE to calculate many environmental outputs as compared to the other tools. These outputs include energy and water consumption, GHG emissions, particulate matter emissions, RCRA hazardous waste produced, as well as human toxicity potentials (both cancerous and non-cancerous).[4] However, the first and only version of PaLATE was developed in 2004,[4] and while the range of environmental outputs of PaLATE is wide, these are limited by potential out-of-date databases. It was found that PaLATE could be updated with relative ease. For instance, recycled asphalt shingles (RAS) was used in significant volumes by several member states, and it was found that PaLATE databases could be updated with relative ease.

Based on the limitations and advantages of each LCA tool, PaLATE was found to be the best suited to accommodate the objectives of this project. Even though there were limitations with PaLATE due to its outdated databases, if the need was found, modifications to its databases could be easily made, unlike the other three LCA tools.

4 MATERIALS ANALYSES

4.1 *Survey Results*

As-let standard bid item quantities of concrete and asphalt pavements were collected from state DOTs when fly ash quantities were not readily available. From these values, the quantities of fly ash used in pavement applications were calculated using the assumptions stated in the following section.

4.2 *Assumptions to Determine Material Quantities*

In order to calculate the quantities of fly ash from as-let quantities of concrete and asphalt pavements, certain design assumptions were made. These assumptions and generalizations needed to be made, as it was impossible to determine specific design parameters (such as pavement thicknesses and fly ash replacement of concrete) for every DOT project over the annual period. Table 4.2.1 lists the assumptions made in order to calculate the quantities of fly ash used by each member DOT. General assumptions made when running the LCA analysis in PaLATE included:

1. A 1:1 replacement of cement with fly ash was assumed, despite the known varying mechanical properties.
2. All materials were assumed to be delivered to site by cement trucks over a one-way distance of 25 miles.

Table 4.2.1: Assumptions made in calculating fly ash use from concrete and asphalt applications, and the time period for which data was used.

State	***Calculation Assumptions for Fly Ash Use***	***Year of Data Reported***
IDOT	All fly ash used as cement replacement	Calendar Year 2012
WisDOT	For Concrete Pavements and Driveways: Pavement thickness is 10 inches (25.4 cm) Unit quantity of fly ash in concrete is 170 lbs/CY (100.85 kg/m^3)	Fiscal Year 2013
MNDOT	Unit quantity of fly ash in concrete is 170 lbs/CY (100.85 kg/m^3)	Calendar Year 2013
PennDOT	Fly ash replacement in cement was 15% Pavement thickness is 10 inches (25.4 cm)	Calendar Year 2013
GADOT	All reported fly ash quantity was used in HMA and none in concrete pavement.	Calendar Year 2013
VDOT	Data forthcoming	Data forthcoming

4.3 *Results of PaLATE*

The quantities of fly ash used by each member state were analyzed in PaLATE to determine any environmental impacts and benefits of the recycled material use. These environmental impacts and resulting benefits were comparatively analyzed using the same exact amounts of cement instead of fly ash in concrete, or in the case of Georgia, straight HMA versus fly ash in HMA. For Georgia DOT, fly ash is almost exclusively in stone matrix asphalt, a mix similar to HMA. For the Georgia analyses without fly ash used, it was assumed that the material processes were consistent with standard HMA mix designs. The different construction processes associated with concrete and asphaltic pavement are therefore appropriately represented in the environmental output measures produced by PaLATE.

Table 4.3.1 shows the breakdown of each environmental parameter analyzed, and the environmental benefits involved with using a portion of fly ash instead of straight cement concrete (or HMA in the case of Georgia). In general, each individual state had equally significant percent changes for each impact parameter except for Georgia DOT, which showed even more improved environmental benefits.

Table 4.3.2 shows the percent change of all five DOTs combined for total environmental benefit measures using fly ash. From Table 4.3.2 it can be seen that the impact parameters of water and energy consumption as well as CO_2 emissions saw a large increase in environmental benefits. The percent savings ranged from 81% to 88%.

Table 4.3.1: PaLATE LCA results comparing use of cement and fly ash in each state.

STATE	PARAMETER	CEMENT* (IF NO FLY ASH USED)	ACTUAL FLY ASH USED	ENVIRONMENTAL SAVINGS	% SAVINGS
WisDOT	Energy (MJ)	148,718,471	28,801,359	119,917,112	80.6%
	Water Consumption (kg)	68,489	8,884	59,605	87.0%
	CO_2 (Mg) = GWP	10,415	2,001	8,414	80.8%
MNDOT	Energy (MJ)	95,421,050	18,479,587	76,941,463	80.6%
	Water Consumption (kg)	43,944	5,700	38,244	87.0%
	CO_2 (Mg) = GWP	6,682	1,284	5,398	80.8%
IDOT	Energy (MJ)	179,423,531	34,747,813	144,675,718	80.6%
	Water Consumption (kg)	82,629	10,718	71,911	87.0%
	CO_2 (Mg) = GWP	12,565	2,414	10,151	80.8%
PennDOT	Energy (MJ)	40,773,603	7,896,364	32,877,239	80.6%
	Water Consumption (kg)	18,777	2,436	16,342	87.0%
	CO_2 (Mg) = GWP	2,855	549	2,307	80.8%
GADOT	Energy (MJ)	23,133,082	1,320,477	21,812,605	94.3%
	Water Consumption (kg)	10,653	37	10,616	99.6%
	CO_2 (Mg) = GWP	1,620	27	1,593	98.3%

Table 4.3.2: Total DOT environmental benefits in using fly ash in concrete.

TOTALS FOR ALL 5 STATES	PARAMETER	CEMENT* (IF NO FLY ASH USED)	ACTUAL FLY ASH USED	ENVIRONMENTAL SAVINGS	% SAVINGS
	Energy (MJ)	487,469,736	91,245,600	396,224,136	81%
	Water Consumption (kg)	224,492	27,776	196,717	88%
	CO_2 (Mg) = GWP	34,137	6,275	27,863	82%

**** Georgia used fly ash almost exclusively in stone matrix asphalt, a mix similar to HMA***

5 FINDINGS

5.1 *LCA Tool*

The large number of materials, equipment and environmental outputs in the PaLATE database, as well as our familiarity and experience, led to PaLATE being chosen as the main LCA tool to be used and further developed in this project. The four LCA tools researched for this project all had unique advantages and disadvantages, but the disadvantages with PaLATE were easy to overcome, and its advantages out-weighed the use of other tools. The only version of PaLATE was developed in 2004[4], making its databases 10 years old at the start of this project; however, it was found that the databases could be easily updated as needed.

5.2 *Data Collection Tool*

From the surveys and interviews conducted during the course of this study, determining an accurate and simple recycled materials tracking tool proved to be very difficult. Many of the member states had varying personnel, resources and systems in place which makes it hard to implement a standardized materials tracking tool. Some DOTs had a decentralized system making it harder to collect data from many engineers and personnel involved in the data collection process. The means by which our research team calculated fly ash quantities through as-let quantities of concrete (and other materials) worked effectively to project estimated environmental cost savings. This method was determined to be the most practical way to track this data.

5.3 *PaLATE LCA Analysis*

Six member states (GA, IL, MN, PA, VA (Pending) and WI) provided the quantities of fly ash used throughout the system over a one-year period. The environmental effects of using fly ash in pavement construction were then analyzed using the LCA tool PaLATE and were compared to a reference analysis in which the total volume of fly ash was replaced by an equal volume of cement. Overwhelmingly, the use of fly ash in pavement construction decreased the environmental impacts in all three parameters measured by PaLATE, showing average environmental impacts savings between 81% and 88%.

The results of the analyses are also in agreement with the recent EPA ruling (December 2014) that established technical requirements for coal combustion residuals' (CCRs) safe disposal into landfills or surface impoundments. This final rule also distinguished between the disposal of CCRs and beneficial use of CCRs, including fly ash used in concrete.[11]

5.4 *Future Analysis*

Future analysis on this project will include VDOT materials. The team will also complete an update of the environmental, material and equipment databases within PaLATE so that RMRC member states and users of PaLATE will have up to date data analyses.

6 CONCLUSIONS

The Recycled Materials Resource Center, with the help of six member DOTs (GA, IL, MN, PA, VA and WI), is working to understand how DOTs can better track recycled materials in order to calculate the life cycle benefits associated with the incorporation of recycled materials and industrial byproducts to highway pavement construction. This study found that the implementation of a standardized tracking system would be difficult due each DOTs unique administrative structure. However, using as-let quantities of concrete and certain design assumptions to calculate fly ash quantities was found to be the most effective and practical means of tracking.

Using the LCA tool PaLATE, this study has established the quantitative environmental benefits of using fly ash in pavement construction. The environmental impact parameters of water and energy consumption as well as CO_2 emissions saw a large increase in environmental benefits. The percent savings ranged consistently from 81% to 88%. Quantifying these benefits may serve as motivation for more DOTs to actively use and track recycled materials in highway applications.

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